Demand-side solutions to climate change mitigation consistent with high levels of wellbeing

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Abstract

Climate mitigation solutions are often evaluated in terms of their costs and potentials. This accounting, however, shortcuts a comprehensive evaluation of how climate solutions affect human well-being, which, at best, may only be crudely related to cost considerations. Here, we systematically list key sectoral mitigation options on the demand side, and categorize them into avoid, shift and improve categories. We show that these options, bridging socio-behavioral, infrastructural and technological domains, can reduce counterfactual sectoral emissions by 50-80% in end use sectors. Based on expert judgement and literature survey, we then evaluate 324 combinations of wellbeing outcomes and demand side options. We find that these are largely beneficial in improving wellbeing across all measures combined (76% have positive, 22% neutral, and 2.4% have negative effects), even though confidence level is low in the social dimensions of wellbeing. Implementing demand-side solution requires i) an understanding of malleable not fixed preferences, ii) consistently measuring and evaluating constituents of wellbeing, and iii) addressing concerns of incumbents in supply-side industries. Our results shift the emphasis in the climate mitigation solution space from supply-side technologies to demand-side service provision.

Main Text

How should we evaluate different climate mitigation strategies? Even for an ambitious 1.5°C target, several mitigation strategies are plausible – from a high dependence on new energy infrastructures, to low-demand pathways, and a breadth of scenarios in between[1]. Evaluating these options mostly from a macroeconomic cost-benefit perspective is relevant, but it fails to reflect the benefits and costs of mitigation strategies from a wellbeing perspective[2]. There are three closely related shortcomings. First, mitigation options on the demand-side, such as shifts in transport patterns and building design, size and use, interact with the wellbeing of end-users and citizens. Evaluating the marginal monetary costs of these measures, if they can be monetized at all, hardly reflects their full impacts. Second, a focus on costs leads to a tendency to preferably evaluate those solutions that have precise costs values attached, neglecting more systemic or uncertain solutions where price tags are difficult to evaluate or not relevant[3]. Third, income and expenditures only reflect a part of wellbeing, and monetary cost evaluations, even if starting from a broader framework, often ignore encompassing views on wellbeing. This critique is not new, and on the aggregate scale, there is agreement among economists and philosophers and other disciplines that metrics like GDP insufficiently reflect wellbeing, and that these must be replaced by more encompassing metrics[4].

These considerations motivate us to ask how to evaluate climate mitigation strategies by explicitly relating them to human wellbeing. This is a considerable challenge, as there is no single straightforward and agreed upon metric of wellbeing. Wellbeing can be considered on macro level, e.g. in 10 country-level wellbeing domains by the OECD[5], and on micro-level, reflected, for example individual constituents of wellbeing[36]. Approaches can also be separated into subjective understandings of wellbeing (given preferences, happiness) and objective ones (life expectancy, eudaimonic metrics) with diverging implications for climate change mitigation[8,9]. According to some leading eudaimonic approaches, wellbeing has several constituents, and that all of these must be met independently to enable a good life[10,11]. Here, we follow this understanding and examine individual metrics and constituents of wellbeing. We first group demand-side climate solutions into avoid, shift, and improve categories, estimate their respective potentials across sectors (Methods), then ask how they improve or harm individual constituents of wellbeing (Table S1), systematically coding their impact on constituents of wellbeing based on literature review (Methods). We find that demand-side solutions harbor considerable potential both for climate change mitigation and improved well-being but remain scarcely applied. We discuss three barriers that hinder the realization of demand-side climate change mitigation options.

Demand-side options can reduce GHG emissions in all end-use sectors by at least 50%

We understand demand-side options as mitigation opportunities that involve individuals or industrial end users of products, services or processes. These are distinct from supply side options that involve changes in energy supply and deployment of carbon dioxide removal technologies that can be considered independent of demand. Demand-side options can be grouped into avoid, shift, and improve categories, constituting a simple analytical framework pertinent for decision makers[12]. Originally applied to the transport sector[13], avoid, shift, and improve categories can also be transferred to other sectors[12,14]. Here, we generalize 'avoid' to all mitigation options that reduce wasteful energy consumption by redesigning service provisioning systems; 'shift' to the switch to already existing competitive low-carbon technologies and service provisioning systems; and 'improve' to improvements in efficiency in existing technologies where adoption by end users plays an important role.

We categorize demand-side mitigation strategies along avoid, shift and improve categories (Figure 1, Table 1). In all sectors, end-use strategies can reduce the majority of emissions, ranging from 41% (6.6 $GtCO_2$) emission reductions in the industry sector (median estimate), to 49% (8.9 $GtCO_2$) in the food sectors, to 69% (5.6 $GtCO_2$) emission reductions in the land transport sector, and 81% (7.1 $GtCO_2$) in the building sector. These numbers are median estimates. Estimates are approximation, as they are simple products of individual assessments for each of the three "avoid", "shift" and "improve" options. If interactions were taken into account, the- full potentials may be higher or lower, independent of relevant barriers to realizing the median potential estimates. Potentials only involve decisions that can be done by end-users, and ignore supply side options, such as the decarbonization of the electricity sector. However, potentials include technology adoption that reduces carbon intensity, e.g., embedded renewable energy in housing and electric vehicles for transport.

We find that improve options contribute the most in building, transport and industry sectors. Examples include efficient building envelope, household appliances, electric cars, and more efficient material and energy use in industrial production. Shift measures are most relevant for transport, in particular modal shift to walking, cycling, and shared pooled mobility; and for food, in particular shift to flexitarian, vegetarian, vegan, or other healthy diets. These are options that require physical infrastructures and choice infrastructures that support low-carbon choices, such as safe and convenient transit corridors, and desirable and affordable meat-free menu options. Of course, they also require end users to adopt these choices, individually and socially. Avoid options are relevant in all sectors. Cities play an additional role, as more compact designs and higher accessibility reduce demand for km travel and car mobility, but also induce lower average floor size and corresponding heating and cooling demand. The lifetime extension of products and more efficient product design also add to avoiding energy use and related emissions. Teleworking is related to high uncertainty with relatively low potential in consequential assessments, but with possibly higher emission reduction potential if COVID-19 experiences induce a more structural shift in working environments from both employees and employers.

Table 1: Demand-side mitigation strategies and potentials over sectors

ector	Gt CO_2 in 2050	Mitigation Strategy	Changes in CO_2 for ASI	References
ousing, leisure nd services Building) otal mitigation otential: 81%, 1 $GtCO_2$)	8.8	**Avoid: Sufficiency of energy and resources** (include Compact city and Nature based solution from Urban sector) *Building design, size and use (behavioral and lifestyle change)*	10-40% **[median: 25%]**	IEA 2020[15]; Ürge-Vorsatz et al. 2020[16]; Niamir et al. 2020[17]; Ahl et al. 2019[18]; IGES et al. 2019[19]; ECF 2018[20]; Virage-énergie 2016[21]
		Shift: Improve access and switch to renewables *On-site renewables, micro-grids, switch to lower carbon fuels and electrification for spaceheating, cooling, cooking, hot water and electrical uses*	30-70% **[median: 50%]**	IEA 2020[15]; Niamir et al. 2020[22]; Mastrucci & Rao 2019[23]; IGES et al. 2019[19]; ECF 2018[20]; Mata et al. 2018[24]; Virage-énergie 2016[21]
		Improve: Efficiency *Improved building envelope, improved building technical systems (for HVAC, cooking and electrical uses), smart home and digitalization, efficient appliances, control systems, clean cooking*	30-70% **[median: 50%]**	IEA 2020[15]; Mata et al. 2020[25]; IGES et al. 2019[19]; Ellsworth-Krebs et al. 2019[26]; ECF 2018[20]; Virage-énergie 2016[21]
obility, ccessibility and ransport) (total itigation otential: 69%, 5 $GtCO_2$)	9.5	**Avoid: Active travel in highly accessible cities; teleworking** supported by compact highly accessible city design and safe infrastructures for pedestrians and cyclists. *Teleworking or telecommuters partially or entirely replace their out-of-home work activities by working at home or at locations close to home*	1-15% **[median: 10%]**	Brand et al. 2020[27]; Creutzig et al. 2015[28] & 2016[2]; Ivanova et al. 2020[29]; Riggs 2020[30];
		Shift: Shared mobility and convenient and safe public transit *Pooled shared mobility with high occupancy and micro-mobility with high lifetime of vehicle stock; convenient rail-based public transit; supported by urban design and transit-oriented development resulting in reduced travel distances; logistic optimization in last-mile freight.*	0-40% **[median: 30%]**	ITF, 2020[31,32]; ITF, 2017[33,34]; Creutzig et al. 2016[2]; ITF, 2016[35]
		Improve: EVs *Electric Vehicles when charged with the electricity generated from medium decarbonized power system (IEA stated policies); Behavior change programs on the socio-economic structures that impede adoption of EV's; the urban structures that enable reduced car dependence and how EV's can assist grids; and the synergies between emerging technologies and shared economy to maximizing the greater benefit of EVs*	30-100% **[median: 50%]**	EEA, 2018[36]; Hill et al 2019[37]; Lutsey 2015; Plötz et al 2017[38]; Khalili et al 2019[39]
utrition	18	**Avoid:** Food waste	8-25%	Poore and

Food) otal mitigation otential: 49%, 9 $GtCO_2$)			**[median: 15%]**	Nemecek, 2018[40]; Schanes et al. 2018[41]; Gunders & Bloom 2017[42] IPCC SRCCL, 2019[43]
		Shift: Animal free protein *Switch to animal free protein sources such as soy, lentils, other pulses and meat substitute products.*	18-87% **[median: 40%]**	Semba et al. 2020[44]; Springmann et al. 2018[45]; Willett et al. 2019[46]; Parodi et al. 2018[47]; IPCC SRCCL, 2019[43]
ndustry otal mitigation otential: 41%, 5 $GtCO_2$)	15.8	**Avoid:** Materials efficient services *Avoid materials via dematerialization, the sharing economy, materials-efficient and lightweight designs, and yield improvements in manufacturing.*	5%-22% **[median: 13%]**	IEA 2020[15,48]; Grubler et al. 2018[49]; Allwood and Cullen, 2015[50]; Carruth et al., 2011[51]
		Avoid: Lifespan extension *Designing products so that their lifetime can be extended through repair, refurbishing, and remanufacturing, instigated via standardisation, modularity and functional segregation.*	3%-7% **[median: 5%]**	IEA 2020[15,48]; Cooper et al. 2014[52]
		Shift: Reuse and recycling *Increasing the re-usability and recyclability of product's components. Example: dismantle old cars and re-use components for repairing other cars*	4%-7% **[median: 5%]**	IEA 2020[15,48]; Ellen MacArthur Foundation, 2019[53]; IEA 2019[54]; Material Economics 2018[55]
		Improve: Energy Efficiency *Reducing the need for energy consumption through the installation of new efficient technologies and through systems and operating practices that contribute to reduce energy needs*	25%-28% **[median: 25%]**	IEA 2020[15,48]; Material Economics 2018[55]
viation otal mitigation otential: 40%, 7 $GtCO_2$)	1.8	**Avoid:** flights *Aviation is of low economic value and demand is highly sensitive to prices. A carbon price of aviation fuel of \$400/tCO_2 would have demand for aviation in 2050.*	0%-47% **[median: 40%]**	IATA 2020[56]; Schäfer et al. 2019[57]; Gossling et al (in review)
hipping otal mitigation otential: 69%, 3 $GtCO_2$)	1.9	**Avoid:** Reduce demand and slow steaming *Shifting supply chains, lower demand for consumption goods, and slow steaming of ships would reduce shipping demand substantially.*	40%-60% **[median: 47%]**	Bouman et al 2017[58], McKinnon 2020[59], ITF, 2018[60]
		Shift: modal shift to train *Shift from ships to long-distance train (especially across the Eurasian continent) reduces GHG emissions, but not more than 1% of expected emissions.*	0%-1% **[median: 1%]**	ITF, 2018[60]
		Improve: Design and power system	30%-50% **[median:**	Bouman et al

		Independent of fuels (supply) better hull design and improved propulsion system can make ships highly more efficient	**40%]**	2017[58], McKinnon 2020[59], ITF, 2018[60]

Opportunities for avoiding excess consumption exist for all end use sectors. Reducing food waste is a prime no-regret option, accounting for 4.4 GtCO2 emissions, or 8% of total annual GHG emissions, if deforestation effects associated with wasted food provision are included[61]. Consumers are the largest source of food waste, and habitual adjustments, such as meal planning, re-use of leftovers, and avoidance of over-preparation reduce associated GHG emissions[41,42]. Reregulation expiration labels is an option for policy makers to disincentive unnecessary disposal of unexpired items[62]. The mitigation potential of food waste reductions globally has been estimated at 0.8-6.0 GtCO2-eq yr-1 by 2050 [43,63].

Diet shifts away from animal protein to plant-based protein, as another demand side strategy is even more impactful in the food sector. Estimated GHG emissions reductions associated with dietary shifts to low meat diets, vegetarian diets, or vegan diets range from 0.7-7.3, 4.3-6.4, and 7.8-8 GtCO2-eq yr-1 by 2050, respectively[20].

The conceptualization of avoid-shift-improve options originated in the transport sector[64]. The transport sector demonstrates the largest divergence between top-down integrated assessment models and aggregation of bottom-up models. A main reason for this divergence is that place-based solutions and those that involve changing social norms and behavioral adaptations are hard to display in IAMs[65]. A plethora of country and city specific solutions, many of the categorized according to avoid and shift (ca. 15% and 18% of measures respectively), is estimated to have the potential to bring GHG emissions in the transport sector down to 2.5GtCO_2[66]. Key avoid strategies involve telecommuting, although total emission savings in land transport are estimated at not more than 1%[67]. For example, COVID-19 confinement induced telecommuting was compensated by more errands with cars, albeit at shorter distances in California[30]. Urban planning, street space rededication, smart logistical systems, and increased street connectivity with smaller distances have the largest potential to reduce need for travel[68,69], with a counterfactual potential of 25% reduction in urban energy use in 2050 only considering newly built cities (repercussion effects in the building sector are included in this estimate)[28]. Improving transport nonetheless has the largest potential, in particular via electrification. In most ambitious transport energy models, a full electrification of land transport and power-to-fuels for aviation and shipping, can completely decarbonize the transport sector, while also decreasing primary energy required per unit of end use energy, in particular in electric land transport[39]. Vehicle leightweighting strategies can also lead to significant emissions savings through improved fuel economy[70].

Avoiding energy use in buildings starts with smaller dwellings that reduce overall demand for lighting and space conditioning and smaller dwellings, shared housing, and building lifespan extension all reduce the overall demand for carbon-intensive building materials such as concrete and steel[71,72]. It also includes designing buildings based on bioclimatic principles to maximise energy demand reduction through nature and building typology (single-family homes versus multi-family buildings), adapting the size of buildings to the size of households redesigning both individual energy end use and building operations: replace artificial light with daylighting[73,74] and use lighting sensors to avoid demand for lumens from artificial light; design passive houses using the thermal mass and smart controllers to avoid demand for space conditioning services[16]; eliminating standby power to reduce energy wasted in appliances/devices (this alone may reduce household energy use by 10%)[75]. 3D printing of buildings further reduces construction waste, optimizes the geometries and minimizes the materials content of structural elements[76]. Overall, 'avoid' potential in the building sector, reducing waste in superfluous floor space, heating and IT equipment, and energy use, is estimated at 10 and 30%, and possibly up to 50%[77]. Improve options, such as energy efficient appliances, insulation, and prosumer renewables on rooftops may similarly reduce GHG emissions, combined, by 50% [30-70%][16,78,79].

While demand-side solutions will change lifestyles, individuals have few opportunities to induce and realize demand-side solutions by themselves. Avoid measures require structural change in organization management (for example: working time models that enable teleworking), spatial structure (mixed use to increase accessibility with active modes), and incentives (taxing high floor space per capita to reduce wasteful resource use). Similar, shift solutions require the availability of new modes of service provision, e.g., by offering shared pooled mobility and high-quality plant-based diets, and regulation that prohibits high-emitting (and otherwise harmful) practices, such as intensive animal farming and instead promote low-carbon solutions, such as R&D spending for meat alternatives. Finally, improve options similarly require policy interventions, such as carbon pricing, banning inefficient heating systems, lightbulbs and cars with internal combustion engine and diesel motor, and mandating market shares of efficient technologies, planning procedures and practices.

Demand-side mitigation strategies improve wellbeing

Based on 406 papers (Table S3-S7), we analyze how sectoral demand-side and service-oriented mitigation strategies influence constituents of wellbeing. We systematically coded whether mitigation strategies for each sector have positive, neutral or negative impact on the 18 constituents of wellbeing introduced in Table S1. We performed expert judgement by a team of 2-4 researchers for each sector, also comprising explicit expertise on social sciences and wellbeing, and internally reviewed by at least 2 other researchers, to code impact in categories from -3 to +3 and substantiated judgement with evidence from the literature (Figure 2a). Confidence in judgement varied, because both scale and multitude of effects vary across the underlying literature. In other cases, literature was missing even when experts assumed relevant effects. Hence, we also provide confidence values, associated with each mitigation-strategy/wellbeing-constituent couple (Figure 2b) and report the confidence values also together with the results of the wellbeing evaluation below. The full table, including level of agreement and evidence and literature substantiating each entry is in the Appendix.

Demand-side mitigation strategies have positive impacts on human wellbeing (high confidence). Our study shows that among all demand-side option effects on wellbeing 76% (246 out of 324) are positive; 21.6% (70 out of 324) are neutral (or not relevant/specify); only 2.4% (8 out of 324) are negative. Active mobility (cycling and walking), efficient buildings and prosumer choices of renewable technologies have the most encompassing beneficial effects on wellbeing with no negative outcome detected. Urban and industry strategies are highly positive overall on wellbeing, but they will also reshape supply-side businesses with transient intermediate negative effects. Shared mobility, as all others, has overall highly beneficial effects on wellbeing, but also displays a few negative consequences, depending on implementation, such as a minor decrease of personal security for patrons of ridesourcing. Differentiation, however, is important. For example, shared pooled mobility provides more urban benefits, and also higher climate change mitigation potential, as compared to ridesourcing.

Positive outcomes on wellbeing are estimated to occur 19 times more often than negative outcomes in response to demand-side mitigation measures. Confidence is in 50% of all cases medium to high (between 3 and 5 on a scale from 0 to 5) but unequally distributed with higher confidence in the physical constituents than in the social constituents of wellbeing.

The highest benefits are observed in air, health and energy (all with high confidence level), food (medium confidence), mobility (high confidence), economic stability (high confidence), and water (medium-high confidence) respectively. Although the relation of demand-side mitigation strategies and the social aspects of human wellbeing is important, this has been less reflected in the literature so far, and hence our assessment finds more neutral/unknown interactions.

Wellbeing improvements are most notable in air quality (0.74 in average across all mitigation options on a scale from -1 to +1), health (0.72), and energy (0.68). These categories are also most substantiated in the literature, often under the framing of co-benefits. In many cases, co-benefits outweigh the mitigation benefits of specific GHG emission reduction strategies. This includes clean cook stoves (e.g., powered by LPG) that can improve livelihoods of more than 40% of the world population by reducing indoor air pollution[80]; it includes co-benefits from improved outdoor air quality in cities resulting from reduced private motorized mobility with combustion and diesel engines, and from more active mobility[81,82], often associated with more accessible environment of compact cities[83]; and it includes a shift away from high-emission diets that would improve public health considerably, especially in high income countries[84].

Food (0.51), mobility (0.46), and water (0.40) are further categories where wellbeing is improved. Only mobility has entries with highest wellbeing ranking for teleworking, compact cities, and urban system approaches. Effects on wellbeing in water and sanitation are mostly coming from building and urban solutions.

Social dimensions, such as communication, social protection, political stability and especially participation are less predominantly represented. An exception is economic stability (0.52), suggesting that demand-side options generate stable opportunities to participate in economic activities. Altogether, the literature on social constituents, in relationship to climate change mitigation, is meagre. However, there is still clear indication that many demand-side mitigation strategies have potential to improve also the social constituents of wellbeing. For example, the predominant contribution of clean cook stoves may relate to wellbeing of women, who require less time for biomass collection and cooking and can better participate in economic and social life[85]. Compact cities and urban system solutions have strong albeit ambiguous effects on wellbeing, and positive outcomes depend on urban design[86,87].

Confidence is highest for the wellbeing dimensions air, health, and mobility, and for the mitigation options compact city, non-motorized transport and building –level sufficiency. The wellbeing dimensions education, shelter, and political stability have lowest confidence, also reflecting a respective scarcity in literature.

Opportunities for avoiding excess consumption exist for all end use sectors. Reducing food waste is a prime no-regret option, accounting for 4.4 GtCO2 emissions, or 8% of total annual GHG emissions, if deforestation effects associated with wasted food provision are included[61]. Consumers are the largest source of food waste, and habitual adjustments, such as meal planning, re-use of leftovers, and avoidance of over-preparation reduce associated GHG emissions[41,42]. Reregulation expiration labels is an option for policy makers to disincentive unnecessary disposal of unexpired items[62]. The mitigation potential of food waste reductions globally has been estimated at 0.8-6.0 GtCO2-eq yr-1 by 2050 [43,63].

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Positive outcomes on wellbeing are estimated to occur 19 times more often than negative outcomes in response to demand-side mitigation measures. Confidence is in 50% of all cases medium to high (between 3 and 5 on a scale from 0 to 5) but unequally distributed with higher confidence in the physical constituents than in the social constituents of wellbeing.

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Wellbeing improvements are most notable in air quality (0.74 in average across all mitigation options on a scale from -1 to +1), health (0.72), and energy (0.68). These categories are also most substantiated in the literature, often under the framing of co-benefits. In many cases, co-benefits outweigh the mitigation benefits of specific GHG emission reduction strategies. This includes clean cook stoves (e.g., powered by LPG) that can improve livelihoods of more than 40% of the world population by reducing indoor air pollution[80]; it includes co-benefits from improved outdoor air quality in cities resulting from reduced private motorized mobility with combustion and diesel engines, and from more active mobility[81,82], often associated with more accessible environment of compact cities[83]; and it includes a shift away from high-emission diets that would improve public health considerably, especially in high income countries[84].

Food (0.51), mobility (0.46), and water (0.40) are further categories where wellbeing is improved. Only mobility has entries with highest wellbeing ranking for teleworking, compact cities, and urban system approaches. Effects on wellbeing in water and sanitation are mostly coming from building and urban solutions.

Social dimensions, such as communication, social protection, political stability and especially participation are less predominantly represented. An exception is economic stability (0.52), suggesting that demand-side options generate stable opportunities to participate in economic activities. Altogether, the literature on social constituents, in relationship to climate change mitigation, is meagre. However, there is still clear indication that many demand-side mitigation strategies have potential to improve also the social constituents of wellbeing. For example, the predominant contribution of clean cook stoves may relate to wellbeing of women, who require less time for biomass collection and cooking and can better participate in economic and social life[85]. Compact cities and urban system solutions have strong albeit ambiguous effects on wellbeing, and positive outcomes depend on urban design[86,87].

Confidence is highest for the wellbeing dimensions air, health, and mobility, and for the mitigation options compact city, non-motorized transport and building –level sufficiency. The wellbeing dimensions education, shelter, and political stability have lowest confidence, also reflecting a respective scarcity in literature.

Table 2. Assuming preferences to be exogenous or endogenous has impact on the evaluation of solutions.

	Supply-side solutions	Demand-side solution
Exogenous preferences	Current patterns of service provisions are appropriate and new technologies must substitute current supply-side technologies closely.	Making existing technologies more efficient (improve) are appropriate, but shifting or reducing consumption patterns are insufficiently considered. Social dynamics often directed to enable overconsumption.
Endogenous preferences	Lack of orientation on what should be produced; alternative (partially objective) metrics required.	Societies can choose to modify service provisioning systems and lifestyles; alternative metrics and institutions required.

Climate mitigation as if people matter

Our results matter for the core challenge of climate change mitigation. Even the most optimistic upscaling of low-carbon technologies, such as PV[115], alone would be sufficient to meet currently projected energy demand in 2050, as approximately required by the Paris agreement. Demand-side reduction strategies hence provide essential breathing space needed for meeting climate targets in the short and medium term. They are also consistent with improved wellbeing, and more likely to protect non-climate planetary boundaries.

Further research on higher resolution on service provisioning systems that reduce GHG emissions while maintaining or improving constituents of wellbeing will be highly policy-relevant. A new configuration of work and service provisioning models consistent with low GHG emissions and resource demand can only be achieved by transitioning away from the current constellation of service provision models. This requires a paradigm shift in understanding that preferences of what constitutes a good life can change; it also necessitates a change of focus in modelling studies. Starting with a perspective on what people need for a good life adds compelling options to the space of climate change mitigation solutions.

Methods

Assessment approach for potentials. We assessed demand-side potentials and wellbeing by a team of experts for each sector. We hosted three workshops (two in person, one virtual) with the objective of defining and structuring demand-side mitigation strategies. Sectoral experts identified 3 or 4 comprehensive demand-side strategies for each sector and searched, screened and coded the relevant literatures in two domains. First, from the sector-specific scenario and option literature, reductions potential estimates and ranges were systematically extracted. We organized demand side mitigation options according to sectors (building, transport, food, industry) and according to mitigation strategy (avoid, shift, improve) (summary in Table 1; full details given in Table S2). Out of more than 400 papers screened, we selected 98 that support estimates for mitigation potentials for 2050 and were within the scope of demand-side mitigation scenarios (Table S2).

Measuring wellbeing. The literature on human well-being is complicated by varying definitions and overlapping terminology. Terms such as 'human needs', 'well-being', 'subjective well-being', 'happiness', 'welfare' and 'quality of life' are often used interchangeably and imprecisely. A widely perceived divide separates well-being concepts into three broad camps: preference satisfaction, hedonic and eudaimonic positions[6,7] with diverging implications for climate change mitigation[8,9]. The preference satisfaction position, as introduced above, takes citizens' preferences satisfaction as constituting wellbeing and is therefore in some form committed to the view that whatever people choose makes them better off. It is hence closely related to associating higher income with higher well-being, and typically measures the degree to which preferences are satisfied in market transactions and beyond markets as income. Second, in the hedonic view, well-being is a matter of maximizing individuals' happiness, or health. It can be measured for example, via 'life satisfaction' and 'happiness' surveys, and is often interpreted as the subjective perception of well-being conditions in society. A great deal of research examines the individual and social determinants of variation in happiness, health and life satisfaction. This approach builds upon utilitarian philosophy.

A third category of 'eudaimonic' concepts focus on objective conditions and actions that underpin well-being. This constitutes a large family of theories, most notably on 'capabilities'[10,116], 'human needs'[11,117,118], multi-dimensional poverty[119] and so forth. The core claim is to identify and separate a universal set of basic conditions that are required by all humans for a good life, from their satisfiers, which can be culturally and individually diverse. We adopt the 'eudaimonic' position on well-being by the analysis that follows, because of two reasons. First, a eudaimonic approach is consistent with changing preferences, as the focus is on substantive conditions of a good life that are independent of changing preferences (nonetheless, even if preferences are changing, demand-side solutions could also be evaluated by approaches that account for fundamental preferences[120–122]). Second, a eudaimonic approach is largely underrepresented in the context of climate change mitigation, as the current literature evaluating climate policies and measures is nearly exclusively taking an implicit or explicit given preference approach, often shortcut with economic growth metrics.

Despite the very diverse nature of the literature on eudaimonic wellbeing, broad surveys have centered on a number core conditions that achieve consensus across epistemic divides[8,123]. The constituents of eudaimonic wellbeing include essential material conditions of a good life, such as food and energy, but also clean water, sanitation, air quality, and also social dimensions, such as social cohesion and political stability (Table S1). Importantly, these constituents are nearly all reflected in the SDGs (Table S1), and thus have political legitimacy among nations worldwide.

Assessing effects on wellbeing. In a second and separate process, we used sectoral expert judgement and a concurrent literature search on 324 combinations of wellbeing and demand-side measures used to create Table 1. While not all combinations were judged relevant, we supported judgements for existing relationships between demand-side options and wellbeing with 342 references. Experts identified potentially relevant publications through a mixture of their in-depth knowledge of the field and targeted keyword-based queries in relevant bibliographic databases. In addition, in order to develop our key findings, expert teams evaluated the associated *evidence*, *agreement* and *confidence* levels of each entry. *Confidence* in the validity of a finding, based on the type, amount, quality, and consistency of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of *agreement* (for more information see table S3). Further, all steps were subjected to three rounds of internal review including social scientists, wellbeing, and sector- and domain-specific experts (Table S3-7). To also reflect the state of the literature, reflecting highly different literature bases on the combination of wellbeing dimensions and demand-side measures, and to represent uncertainty in interpretation of the literature, we also coded for the confidence of wellbeing impacts in all 324 combinations (Figure 2).

In detail, five sectoral tables are designed: Building, Food, Transport, Urban and Industry (see Table S3-7). The potential of each demand-side mitigation strategy on wellbeing dimensions are evaluated by expert teams based on the existing literature and experts scientific judgments. The impact is coded = {-3, -2, -1, 0, +1, +2, +3} while +3 stands for high positive and -3 high negative impact. In addition, in order to develop our key findings, expert teams evaluated the associated evidence, agreement and confidence levels of each entry. Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement.

The level of evidence {limited, medium, robust}, and degree of agreement {low, medium, high}, presented by **3** and ▯ respectively in the TablesS2-6, are evaluated by sectoral expert teams based on the amount, quality and consistency of evidence. The level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high; presented by ▯ in the Tables S3-7. It synthesizes the expert teams' judgments about the validity of findings as determined through evaluation of evidence and agreement.

Declarations

Data availability statement. All data used for Figure 1 and Figure 2 are fully presented in the SI – Extended data.

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Figures

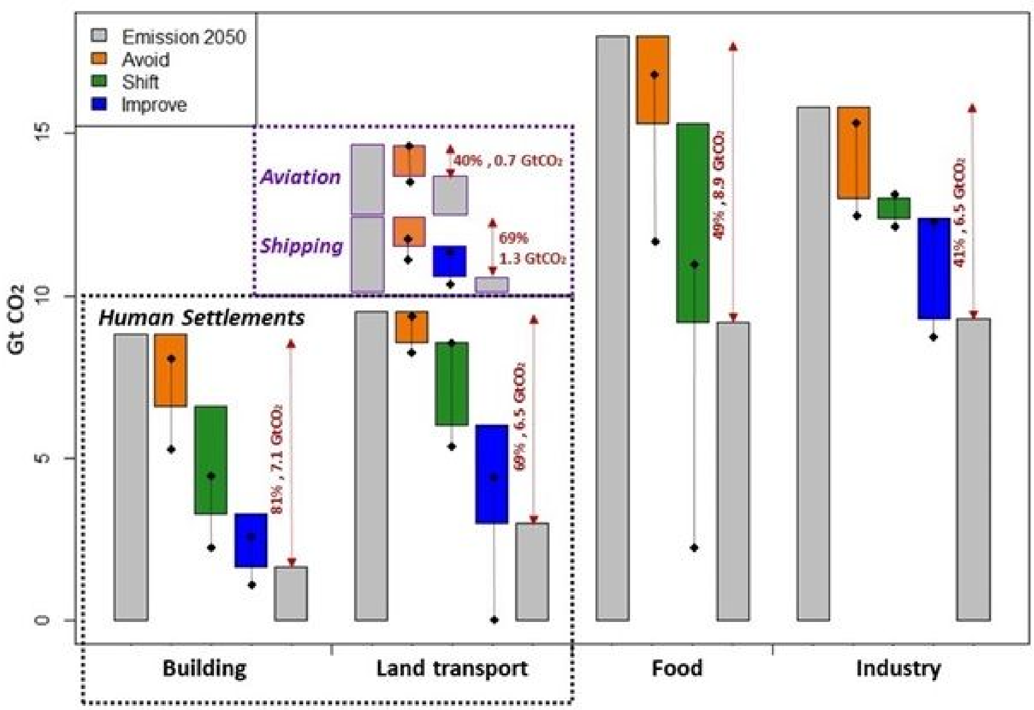

Figure 1

Potentials in end-use sector classified in avoid, shift, and improve options. We reviewed studies estimating demand-side potentials associated with demand-side GHG avoid, shift, and improve emission reduction strategies and summarized results as median values and full ranges (minimal to maximal potential). To be able to give approximation for the full potential across sectors, we ignore interaction effects between the three categories. Potentials are estimated against 2050 values of IEA's stated policy scenario15. Data sources and explanations: see Table 1 and Table S2.

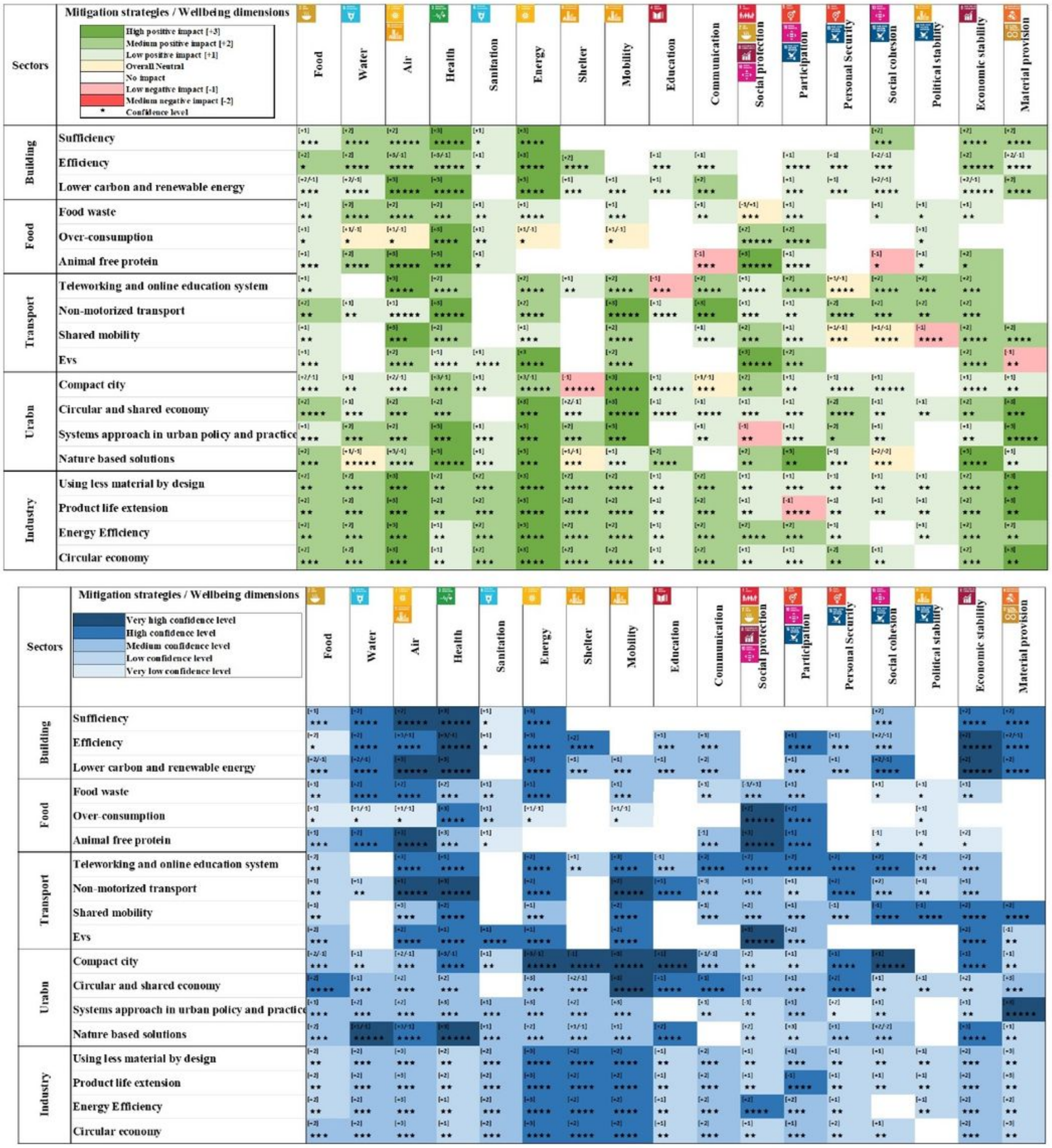

Figure 2

Effects of demand-side options on wellbeing in 19 different categories. A) Magnitude and direction of wellbeing effect. B) Confidence of assessment in demand-side option/wellbeing rating, based on the state of the literature. Detailed data underpinning the assessment is reported in Tables S3-S7.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformationv04.pdf